In the thermal-spray coating process, the coating material is melted in a heat source. The molten material is then propelled by process gases and sprayed onto the base material. The particles impact on the base material, also known as the substrate, solidify, and form a solid layer. This process includes complex multiphase flow with disperse particles, heat transfer, and conversion of thermal to kinetic energy. In plasma guns used for thermal spray, the temperature in the plume can reach 16,000 K, which makes measurements of the gas flow field extremely challenging. Computational fluid dynamics (CFD) permit the examination of plasma-gun behavior in operating regimes never before explored.
The use of plasma guns—plasma is an ionized gas—for thermal-spray coatings is several decades old, and these guns have since matured into efficient coating tools. In plasma guns, an arc is established between an anode and a cathode (Fig. 1). The gas flowing between the electrodes is ionized such that a plasma plume develops. The spray material is injected as powder outside the nozzle into the plasma plume, where it is simultaneously melted and accelerated toward the substrate surface. Keeping the plasma stable under a wide range of operating conditions, which includes various types of gasses and their interaction, has proven to be a considerable design challenge.

**Important Design Tool**

Industrial users of plasma thermal spray demand reduced costs by increasing production rate, increasing deposit efficiency, and extending hardware life. Today, CFD is at a point where it can serve as a design and development tool to dramatically improve the operation of a plasma gun. CFD also permits the examination of plasma gun behavior in untested operating regimes in order to extend their application range and develop new and better coatings (Fig. 2). Previously, the development and improvement of process gun hardware for thermal spray was done by empirical trial and error. Engineers and scientists would surmise what was happening inside the gun, propose solutions or improvements, manufacture parts, and test the changes. This process was often time consuming and costly. A month of CFD work can literally replace a year’s worth of physical prototyping and yield better results.

The Sulzer Metco TriplexPro™-200 plasma gun is an ideal platform for the application of CFD to improve gun performance (Fig. 3). Its 3 arcs permit a wider range of current, and the gun is robust enough to handle extreme operating conditions when tested at its limits. The design also facilitates the separation of gas flow and arc control, permitting a wide range of gas flow within the voltage limits of the support equipment. Finally, the turbulence level is significantly lower than in the turbulent gas flow typical for other plasma guns.

![Plasma gun diagram](image)

**1** Gas flow in the nozzle of plasma spray guns and powder injection into the plasma plume are 2 areas where Sulzer Metco applies CFD to improve gun performance.

![Operating window comparison](image)

**2** The current operating window of the TriplexPro-200™ gun extends past the operating range of typical plasma guns on all fronts.
Systematic Modeling

The overall dynamics of a plasma gun are complex, and modeling them requires a step-by-step method. First, the model of the gas dynamics was developed assuming uniform gas temperature and validated against measurements of the TriplexPro gun instrumented for registering back pressure and flow. Once it had been confirmed that the isothermal model simulated the actual pressure and flow field in the gun, a model of the electric arcs, complete with magnetic field, was added to the gas model to heat the gas. Again, the model was validated with the actual TriplexPro gun under operating conditions of flow and pressure, now also including voltage and current. Next, the injection of powder particles into the plasma plume was included in the simulation and validated with particle temperature and velocity profiles, using an Accuraspray™ particle diagnostic system and custom high-speed imaging equipment. To complete the model, the mass of the gun was configured with thermodynamic properties, which were validated using the energy losses in the water cooling circuit as well as surface temperature measurements.

CFD Supports Development

The TriplexPro-200 plasma gun comes with 3 nozzles (Fig. 4) that encompass a wider operating range than typical plasma guns. A wide bore, high-enthalpy nozzle produces a slow and hot plasma plume, a medium bore produces a plasma plume typical of most plasma guns, and a narrow bore convergent-divergent supersonic nozzle produces a fast and cool plasma plume. The use of CFD enables customization of each type of nozzle in terms of gas flow. Incorporating a model of the arcs into the CFD model permits further improvements to produce a stable and uniform arc pattern. The stability of the arc heats the gas evenly and assures that the arcs remain predictable over a wide range of gas flows. Further, CFD modeling supports the development of more unconventional nozzles, which allow for shaping of the plasma plume to extend the range of applications.
Product Improvement
An example of a CFD-based improvement that quickly made it into the production gun was an improvement in the convergent-divergent HV nozzle itself. The original 5-mm nozzle was designed to produce supersonic plasma velocities. The formation of shock diamonds in the plasma plume was an indicator that this goal had been achieved. However, the edges of the plume exiting through the divergent section of the nozzle appeared fuzzy—as if the plume was out of focus. The CFD-model images clearly showed that, with ideal operating gas flows, the gas flow separated from the diverging nozzle wall approximately two-thirds of the way downstream of the nozzle throat (Fig. 5), creating a turbulent region between the main gas flow and nozzle wall. This flow separation indicated that the nozzle was over-expanded. Once the problem had been identified, the nozzle design was changed to shorten the nozzle divergent section, a measure that reduced the Mach number, and thus eliminated the overexpansion (Fig. 6). This modification both further stabilized the plume and reduced energy loss.

Further Enhancement Expected
Sulzer Metco’s TriplexPro-200 plasma gun has already benefited from the results of CFD modeling. With this tool and the expertise of Sulzer engineers, the potential to further improve the design not only of this gun but also of conventional plasma guns is significant. As plasma guns, in general, are less than 15% efficient in applying the energy input to the coating process itself, there is considerable room for further improvement. Further CFD-based improvements will concentrate on increasing efficiency and throughput. The potential for higher operating power levels, as well as higher gas velocities and temperatures has already been demonstrated in the models using the same basic gun design. The future of plasma thermal spray looks very bright.

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5 A close-up of the CFD-model with the 5-mm nozzle clearly shows the formation of shock diamonds as they appear in the actual gun as well as the flow separation from the wall of the divergent section of the nozzle.

6 The 5-mm nozzle before and after modification as a result of the CFD gas flow model analysis. Note that the nozzle is shorter but retains the same geometry as the original nozzle.
The Lorentz force is essential when fluid mechanics and electro-magnetic forces have to be coupled. An electric field is defined by the forces between non-moving charges, whereas a magnetic field is created by moving charges. In the plasma spray gun Triplex-Pro™ by Sulzer Metco, the fluid that is moving in an external electric field causes a current density \( \mathbf{j} \), which comprises of 3 electric arcs and in turn causes a magnetic field. The interaction of the magnetic field with the current density causes the Lorentz force \( \mathbf{f} = \mathbf{j} \times \mathbf{B} \), which is exerted on the 3 arcs. The current is aligned along the main axis, and the magnetic field is orientated clockwise concentrically around the current, therefore the resulting Lorentz force points inward, according to the right-hand rule. If this effect is considered in the simulation, the singular arcs contract and the temperature distribution in the fluid at the nozzle outlet becomes axially centered and homogeneous. The flow simulation without (left) and allowing for the Lorentz force (right) clearly shows this effect. The electric arcs end at the nozzle outlet, whereas the heated plasma plume exits the spray gun.